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PREDICTION MODEL FOR ESTIMATING PERFORMANCE IMPACTS OF MAINTENANCE STRESS

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Janet Taynor
Gary A. Klein

Klein Associates, Incorporated
P.O. Box 264
Yellow Springs, Ohio 45387

Cheryl L. Batchelor

LOGISTICS AND HUMAN FACTORS DIVISION
Wright-Patterson Air Force Base, Ohio 45433-6503

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An Identification Point modelling tool was constructed to assist Air Force planners to predict the effects of stress upon aircraft maintenance time. ~~Five variables in a factorial design defined the model.~~ Preparedness for the hazard, experience of the maintenance technicians, payoff for performing the task quickly, task complexity, and the need for others to complete the task were combined to produce 32 identification points in the model. The Comparison Based Prediction method was used to obtain information from maintenance experts in industry, Air National Guard experts, and civilian fire vehicle maintainers. The model describes and predicts the effects upon maintenance time of various combinations of the five factors.

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Janet Taynor
Gary A. Klein

Klein Associates, Incorporated
P.O. Box 264
Yellow Springs, Ohio 45387

Cheryl L. Batchelor

LOGISTICS AND HUMAN FACTORS DIVISION
Wright-Patterson Air Force Base, Ohio 45433-6503

Reviewed and submitted for publication by

Robert C. Johnson
Chief, Combat Logistics Branch

This publication is primarily a working paper. It is published solely to document work performed.

SUMMARY

An Identification Point Model was constructed to assist Air Force planners in predicting the effects of stress upon aircraft maintenance time. Relevant causal factors that would result in an increase or decrease in maintenance time were identified. A prototype of a prediction tool was described that utilizes these factors.

The use of this tool in two modest studies yielded 41 predictions for the situation in which adequate preparations could be made for the hazardous situation. Three more data points were collected for a situation in which preparation could not be made.

Suggestions were made about enhancement and further use of the Identification Point Model.

PREFACE

The work reported in this technical paper was performed by Klein Associates under subcontract from RJO Enterprises, Inc., Dayton, Ohio. The work was accomplished under ASD contract F33657-84-D-0315-0011/PTD 0315-RL02-10-03 for the Air Force Human Resources Laboratory (AFHRL). Ms. Cheryl L. Batchelor monitored this subcontract for the Laboratory.

This effort is a portion of the AFHRL Maintenance and Combat Support thrust and the Combat Logistics Systems subthrust, and is specifically a part of the Maintenance Readiness task. It supports the Laboratory's interest in the impact of combat stress on the capabilities of a maintenance organization. This is a follow-on effort to further develop a methodology developed by Klein Associates to quantify the impact on stress on the performance of technical tasks.

Klein Associates acknowledges the valuable assistance of Chief Randy Staley, David Looney and Tim Parks of the Washington Township Fire Department of Centerville, OH for providing insight into their sometimes stressful environment. The support provided by these individuals permitted access to valid data sources and, therefore, contributed immensely to the quality of this paper. Klein Associates also wishes to thank Mr. Marvin Thordsen for his assistance in collecting data and Ms. Beth Crandall for her critical review of earlier drafts of this paper.

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Prediction Model for Estimating Performance Impacts
of Maintenance Stress

I. INTRODUCTION

Future combat conditions may expose maintenance technicians to hazards such as bombs, bullets, and nuclear/biological/chemical (NBC) warfare conditions. The speed and manner of aircraft maintenance task performance under these conditions are critical determinants of how fast aircraft can be returned to combat. The speed at which aircraft can be turned around during normal operations and during simulated surge conditions can be studied and the data used to calculate sortie rates. ~~However, such study methods do not address the effects of~~ performing ~~maintenance in~~ life-threatening environments. The study of performance of even routine maintenance tasks in this type of environment must take into account the effects of psychological stress.

Because the effects of psychological stress upon maintenance personnel can have a critical impact upon the time needed to return aircraft to battle, the effect of such stress must be addressed. Unless the real and/or perceived stress upon maintenance personnel is accounted for, this important variable may upset all calculations about sortie rates and negate the effectiveness of many formal planning efforts.

The purpose of this paper is to describe the prototype of a tool intended to assist the Air Force in predicting the effects of psychological stress upon maintenance time.

In the first phase of this effort, data were collected from experienced maintenance personnel in hazardous chemical plants and maintenance officers from the Air National Guard to estimate and predict maintenance time in Air Force combat conditions. The Comparison Based Prediction (CBP) method was used to structure and elicit expert judgments and predictions about maintenance time. It was found that maintenance tasks generally were predicted to take 20% longer in stressful conditions. Causal factors that were relevant to the performance of technical tasks under stressful conditions were identified. A follow-on project used this information (and collected some additional data) to model the effects of stress upon maintenance time.

The Comparison Based Prediction Method

The CBP method was developed by Klein Associates as a prediction method. CBP has proved to be successful in situations characterized by ambiguous or missing data or uncertainty about critical elements of the prediction scenario (John, Klein, & Taynor, 1986; John, Strobhar, & Klein, 1986; Klein, 1982; Klein & John, 1985; Klein & John, 1986; Klein & Weitzenfeld, 1982; Klein & Williams, 1983). Formally, it is a system of reasoning by analogy, predicting

to an unknown case by drawing upon what is known about a familiar, comparable case. Empirically, it is a means of significantly increasing the validity and reliability of very difficult predictions. Operationally, it is a way to make predictions in situations in which other methods do not appear useful.

In obtaining predictions, the CBP method capitalizes upon the natural human analogical reasoning process. Most typically, the predictions are made by experts in the content domain of interest. The process by which they make their predictions is structured and probed so that the causal factors most salient in both the analog and the problem at hand are highlighted and documented. Because the causal factors drive the predictions, they are documented such that the reasoning employed by the experts can be made explicit to others. If errors have been made, or an inappropriate analog chosen, this also is made apparent by the audit trail of how and why the prediction was made.

Previously, the method has been used in a face-to-face interview format. Currently, under sponsorship of the U.S. Air Force Weapons Laboratory at Kirtland Air Force Base, CBP is being used in conjunction with a decision aid to enhance survivability analysts' predictions of the survivability of structures after a nuclear blast.

II. BACKGROUND

In 1986, Klein Associates, sponsored by the Air Force Human Resources Laboratory, Combat Logistics Branch (AFHRL/LRC), conducted a study to assess the impact of psychological stress upon aircraft maintenance task times. Using the CBP method, data were collected from 32 expert civilian and Air National Guard maintenance personnel to predict the time required for Air Force aircraft maintenance personnel to perform maintenance tasks in a stressful combat scenario. The results of this study were reported by Klein and John (1986).

The findings of that report revealed that the subject-matter experts (SMEs) of that study predicted aircraft maintenance time for Air Force personnel in a combat scenario to be degraded by an average of 20%. When the tasks themselves were examined more closely, it was found that the 20% deceleration in aircraft maintenance task time was a feature of complex tasks. When the tasks were of a more routine or simple nature, the findings were more complicated. Civilian and Air National Guard SMEs did not agree about predicted maintenance times for simple tasks. Civilian SMEs predicted the simple tasks to show no deceleration whereas the Air National Guard SMEs predicted a 40% deceleration in aircraft maintenance task times.

The divergence of predictions between simple and complex tasks, plus the additional difference between Air National Guard and civilian SMEs' predictions for simple tasks, suggested that a variety of factors were operating in producing predictions of maintenance time. Knowing that each expert worked from his own unique experience base, his own assumptions about the combat

scenario, and his assumptions about how combat conditions would differ from his own experience, it was suspected that the causal factors that produced the predictions would differ across experts. The audit trails from the CBP process confirmed this. The experts' assumptions about the combat scenario and how that differed from their own experience base, indeed, did affect the predictions they made about the effects of stress upon maintenance time in combat situations.

Having learned that, even in this small database, the relationship between stress and maintenance time was a multifaceted one, another study was undertaken to determine the nature of those relationships and construct a model that would describe and predict the effects of stress upon aircraft maintenance task times.

III. BUILDING THE MODEL

First thoughts about a model to describe the relationship between stress and maintainer time focused upon building a mathematical model. It was anticipated that the relevant factors would be identified, weighted, and combined into an equation that would describe and predict the relationship between stress and maintenance time.

When building a mathematical model, one can do so in several ways. An empirical approach may be taken in which the model is based upon one data set and subsequently tested on a different data set. This approach requires large databases, especially if the model contains more than two or three factors.

Another approach, on a more conceptual level, is appropriate for small databases such as the one at hand. This approach is viable when there are a small number of factors and when the relationship among the factors is fairly straightforward (linear as opposed to curvilinear). It had been thought that these assumptions could be met, so, the intention was to examine the available data and construct a simple algebraic formula to describe and predict performance time.

A model was envisioned that looked something like the following:

$$Y = ax(1) + bx(2) + cx(3) + dx(4) + ex(5),$$

where Y = maintenance time, expressed as a percentage increase or decrease from non-wartime and non-stress conditions,
a = preparedness for the hazard,
b = experience of technicians,
c = complexity of the task,

and so on.

Toward this end, the data were re-examined to identify a pattern for the factors that were reported to affect maintainer performance time.

The CBP method was used in the earlier study to elicit expert opinion from the SMEs. The SMEs had been asked to describe a maintenance task they had performed in which there had been real danger to themselves or others. Their task had been to state whether they accomplished the task more rapidly or more slowly in the emergency condition (as opposed to normal circumstances) and to describe the causal factors they perceived to be responsible for that time difference. They then were asked to consider a combat scenario and to make a judgment about whether maintenance time would be accelerated or decelerated in that situation. Again, they were called upon to state the factors that they perceived to be responsible for their judgments.

As will be recalled from the original study, SMEs cited 11 factors that differentiated the change in maintenance time between their own experience and the combat scenario for which they were asked to make a prediction. (Table 1 depicts these causal factors and the number of times each was cited.)

Table 1. Industry SMEs' Use of Factors Differentiating Air Force From Industry

Factors	Number of SMEs citing increment
Chance to adapt to emergency condition	10
Nature of hazard	9
Type and experience of technicians	8
Consequence of delays	6
Information on hazard	6
Complexity of task	5
Level of coordination needed	4
Precautionary measures	4
Opportunity to self-select volunteers	3
Nature of protective equipment	1
Reaction time to communications	1

Careful scrutiny of the causal factors resulted in several observations. First, the factors are not independent or distinct from one another. Second, the presence of one factor quite often implies the presence of another. (For example, the "nature of hazard" would dictate whether or not "precautionary measures" could be taken.) Third, some of the factors are very general in nature ("nature of hazard") and others are more specific ("opportunity to self-select volunteers").

Because of these observations, the 11 obtained causal factors were collapsed into four factors believed to be a clearer representation of the data. The robust nature of these factors was confirmed by examining how the SMEs used them, ascertaining the number of times each factor had been cited, and determining the deceleration in maintenance time attributed to each factor. (See Table 2 for the categorization of causal factors, the frequency of their use, and the decelerated maintenance time attributed to each.) At this point, the AFHRL contract monitors were consulted about our

preliminary thinking and they suggested a fifth factor they thought to be important in describing the relationship between stress and maintenance performance.

The resulting five factors were:

- preparedness for the hazard,
- task complexity,
- experience of technicians,
- payoff for speed, and
- need for others.

Table 2. Causal Factors Differentiating Predicted Air Force and Industry Maintenance Times in Emergency Conditions Reported by Air National Guard and Industry Subject-Matter Experts

Air National Guard			Industry		
Factor	Frequency	% Deceleration	Factor	Frequency	% Deceleration
Prepare for Hazard[a]	3	46%	Prepare for Hazard[b]	29	53%
Task Complexity	2	40%	Task Complexity	5	7%
Type and Experience of Technician	2	25%	Type and Experience of Technicians	3	5%
Payoff for Speed	1	-33%	Payoff for Speed	6	-47%
			Level of Coordination[c]	[illegible]	8%
			Opportunity to Self-Select Volunteers[c]	3	9%

[a]This represents a combination of the categories of: NATURE OF HAZARD and CHANCE TO ADAPT TO EMERGENCY CONDITIONS.

[b]This represents a combination of the categories of NATURE OF HAZARD, CHANCE TO ADAPT TO EMERGENCY CONDITIONS, PRECAUTIONARY MEASURES, and INFORMATION ON HAZARD.

[c]Level of Coordination and Opportunity to Select Volunteers were dropped because of their low frequency and low impact upon maintenance time.

Thus, the causal factors identified by the CBP process in the previous study had been reduced to five critical variables. (Table 3 depicts the resulting five factors that experts in maintenance performance reported to affect maintainer performance time.) The next task was to use these building blocks in such a way that the relationships between stress and maintenance time could be described and predicted.

Table 3. Causal Factors Affecting Aircraft Maintenance Time

Causal factors

Prepare for hazard
- nature/seriousness
- chance to acclimate
- able to take precautions
- information on hazard

Task Complexity

Experience of Technicians

Payoff for Speed

Need Others to Complete Task

→ 20% increase in time to complete task

INDUSTRY SME estimates: For COMPLEX TASKS = 20%
For SIMPLE TASKS = 0%

Air National Guard estimates: For COMPLEX TASKS = [illegible]0%
For SIMPLE TASKS = 40%[a]

[a]One SME involved in this judgment

The efforts then returned to building a mathematical model to accomplish this task. However, a number of issues emerged concerning the soundness of trying to capture this phenomenon with a mathematical model. As the original 11 causal factors were scrutinized, doubt was raised about whether the data could meet even the simple operating guidelines calling for a small number of independent factors and linear functions to describe relationships among the factors. Even after collapsing the 11 factors into five, the resulting five factors were not independent. (For example, most of the complex tasks in the original study required others to accomplish them.) Nor was the shape of the relationship among the factors known. (For example, consider the factors of the experience of the technician and the complexity of the task they are asked to perform. To a certain point, the more experience a technician has, the less complex the task will be for that person; that is, because his experience has led him through many complex tasks, such tasks are not as complicated to [illegible]e. However, there is a point where a task

is sufficiently complex that even the most experienced technician will find it so. Therefore, the relationship between experience and task complexity would be linear to the point at which the task is so complicated that it makes no difference how experienced the technician is. Thus, what had been a linear relationship would turn into a curvilinear one when extremely complex tasks were taken into account.)

Equally important to the lack of independent factors is the issue of interacting variables. Consider the situation in which the maintenance task is a simple one. It is reasonable to assume that simple tasks in a combat scenario would be performed faster when the technician could reduce his own exposure to danger by doing so. On the other hand, when the technician would not enhance his own safety by hurrying, there is no reason to predict that the task would be performed any quicker than under normal circumstances.

The original data confirm these expectations. When maintenance experts assumed there would be no payoff for accelerating maintenance time, they predicted simple tasks to take no longer in a combat scenario. When they assumed there was a payoff for hurrying, a 25% acceleration was predicted. This interaction is shown in Table 4.

Table 4. The Interaction Between Task Complexity and Payoff for Speed in Predicting Aircraft Maintenance Time[a]

Task complexity	Payoff for Speed	Maintenance Acceleration
simple	yes	+25%
simple	no	0%

[a]Only the simple task condition is shown.

The complicated nature of the prediction process is not fully captured by the preceding example, however. (The above predictions were made by experienced civilian maintenance personnel who assumed that Air Force maintenance personnel also would be experienced. When an Air National Guard SME made his predictions, he assumed that Air Force maintainers would be inexperienced. When this experience factor is added to the relationship, the process involves three factors and is even more complicated. Table 5 depicts these relationships. Changing the assumption of having experienced technicians to one of having inexperienced technicians changed the sign of the predicted maintenance time!) All of these figures were taken from the original data.

Table 5. The Interactions Among Experience, Task Complexity, and Payoff for Speed in Predicting Aircraft Maintenance Task Time

Experienced technicians	Task complexity	Payoff for speed	Maintenance acceleration
yes	simple	yes	+25%
yes	simple	no	0%
no	simple	yes	-40%

The findings in Table 5 were all obtained for the condition in which others were not needed to accomplish the task. When others are needed to accomplish a simple task, an even more complex pattern emerges involving four factors. The condition in which others are needed to complete the task produced both an accelerated and a decelerated maintenance time, as shown in Table 6.

Table 6. The Interactions Among Need for Others, Experience, Task Complexity, and Payoff for Speed in Predicting Aircraft Maintenance Time

Others needed	Experienced technicians	Task complexity	Payoff for speed	Maintenance acceleration
no	yes	simple	yes	+25%
no	yes	simple	no	0%
no	no	simple	yes	-40%
yes	yes	simple	yes	+53%
yes	yes	simple	no	-16%

Thus, even this limited database shows the importance of modelling the interactions among the factors.

If a mathematical model were attempted, these interactions would have to be represented. Interactions can be described empirically when very large databases are used. It is even possible to model the four- and five-way interactions that would be required to predict the effects of stress upon maintenance time. However, it would require extremely large databases to build and subsequently test the model. Large databases containing this information are not available at the present time. Mathematical modelling from a conceptual standpoint also presents serious difficulties. Five interacting factors strain its capacity.

Because of the problems encountered in meeting the assumptions of a mathematical model, an alternative form of modelling was sought that would capture the fullness of the relationship between stress and maintenance time. A modelling approach was desired that would preserve the power of using expert judgment as a data source, while, at the same time, be sufficiently rigorous to advance our knowledge about the impact of stress on maintenance times.

IV. THE IDENTIFICATION POINT MODEL

In addition to the aforecited goals of conceptual rigor and utilizing expert judgment, the modelling approach had to produce a tool that would be sufficiently structured to allow easy application by the user. It is thought that the model described below accomplishes these objectives. However, when reviewing this type of model, the reader needs to depart from thinking of equations and formulae. Instead, a framework should be set that permits the definition of variables to be somewhat "fuzzy" (as defined by the context in

which they are embedded) while still being uniform enough to maintain sufficient rigor and to have meaning for users of the model.

The tool to be described will be called the "Identification Point Model." The Identification Points (IPs) in the model are the means by which data will be stored in this prediction tool and also the anchor points at which the end user will find answers to questions concerning anticipated changes in maintenance time in a combat situation.

It is intended that this model will allow a user to employ each factor in the model in combination with every other factor. One level of each of the five factors of the model will make up each IP. Thus, each IP will be described by every factor.

When using the model, the users would define their own prediction problem in terms of the factors in the model. For example, the user would determine whether the task was high or low on complexity, whether the need for involvement of others would be high or low, whether the payoff for speed would be high or low, and so forth. In this way, he or she would match the prediction scenario to the appropriate IP. After locating the best-matched IP, the user then would retrieve the empirical evidence, the maintenance time, which had been previously gathered from SMEs and had been stored at each IP.

The type of model proposed here differs from a mathematical formula in several ways. The IP model is a way of categorizing existing data in such a form that the data can be easily retrieved by both sophisticated and novice users. It differs from the traditional mathematical model in that the problem does not require the numerous calculations to make predictions. It does require that a previously acquired information base be sequenced and stored so as to serve as the basis of estimating the effects of stress upon maintenance time. The tool, itself, would channel the user's attention to the most nearly matched IP of the model. Each IP would contain several levels of detail of information, thus giving the user numerical estimates of maintenance time changes and, very importantly, contextual information from which the numbers in the model were derived. Thus, the user would not be relying blindly upon numerical estimates alone.

Before going to an actual example of how the model would be used, its construction from the original data will be described.

Constructing the IPs from the Data

The first step in constructing this model for data storage and retrieval was to identify the IPs of the model. The intent of the model is that each IP will represent a unique combination of factors in the model. That is, one IP in the model would be represented by a high level of each of the five factors. Another IP would represent a low level of the first factor and a high level on each of the remaining four factors. This factorial cycling would continue until each combination of factors was represented. It was decided to make each factor dichotomous in order to keep the model simple and to make the clearest referent points for a user of the model.

The re-examination of the data had indicated that five factors were used by the SMEs when making their estimations of emergency maintenance time. However, the nature of the hazard had been assumed by all the SMEs to be such that the maintainer could prepare for it and/or take precautions against it. In essence, even though they often cited the nature of the hazard as a causal factor, they used only one level of the factor as defined here (that level being the case when precautions could be taken). Because the SMEs had used only one level of this factor, the preliminary analyses in the present effort were confined to the other four factors. When the two levels of each of the four remaining factors were combined (2 x 2 x 2 x 2), a matrix containing 16 IPs was obtained. Each IP in the matrix was assumed to be in the condition in which maintainers could take precautionary measures against the hazard. The IPs are shown in Table 7.

Table 7. The Identification Point Model

Factors	Numerical Classification of Identification Points															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Task Complexity	H	H	L	L	H	H	L	L	H	H	L	L	H	H	L	L
Experienced Techs	H	H	H	H	H	H	H	H	L	L	L	L	L	L	L	L
Payoff for Speed	H	H	H	H	L	L	L	L	H	H	H	H	L	L	L	L
Others Needed	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L

Four of the factors of the model are listed: task complexity, experience of the technicians, payoff for speed, and need for others. "H" stands for the high level of a factor. "L" stands for a low level of a factor. The level of each of the factors at each of the 16 IPs is defined by the column under the IP number. For example, IP #7 is characterized by low task complexity, high experience, low payoff for speed, and high need for others. All data that were collected in which SMEs assumed this unique combination of factors to be operative are represented at this IP.

In the original study SMEs assumed that precautionary measures could be taken for the hazard; so, this factor was not dichotomized in this Table. We will introduce the other level of this factor, that being when the technician could not prepare for the hazard, when we discuss additional data collected in this study.

Assigning Experts' Judgments to the IPs of the Model

The data were examined to determine the best match between the IPs and each case obtained in the study. A case is defined here as an SME's judgment of maintenance time either for his own task as recounted to the interviewers or for the hypothetical combat scenario. A careful examination of all recorded responses of each SME was made in order to determine what that person's assumptions were about each of the factors in the model. After the determination was made of whether each case was high or low on each of the factors, the case was ascribed to the appropriate IP.

Several analyses were conducted. The civilian SMEs' estimations of the change in maintenance time between their own tasks performed in an emergency situation and the same tasks performed under normal circumstances were analyzed (Table 8). The predictions of these same experts for a combat scenario were analyzed (Table 9). The predictions of Air National Guard personnel were tabulated (Table 10). Finally, all the data were combined (Table 11) to obtain a first look at how maintenance time was distributed across the different IPs in the model.

The IPs in Table 11 contain judgments from varying numbers of SMEs, ranging from one per IP to six per IP. Several experts' scores were eliminated (one score from SME 5, one from SME 12, and one from SME 16) because they could not be categorized along all four factors with any degree of certainty. Two data elements were changed from the way they had been erroneously scored in the first report (SME 2's description of differences between normal and emergency conditions and SME 4's Air Force prediction). Two data elements were added because two experts (SME 6 and SME 18) distinguished between experienced and nonexperienced personnel, reporting corresponding numerical estimates of maintenance time.

Table 11 allows a first look at how well the model organizes the data and a preview of its potential predictive power. Eleven of the 16 IPs in Table 11 contain data. The vestiges of the findings of the earlier report can be seen. At IP 8 where the task is simple, is performed by experienced technicians, has a low payoff for speed, and does not need others to perform the task, no change in maintenance time is seen. This corresponds to the first report. At IP 5, where the task is complex, is performed by experienced technicians, has a low payoff for speed, and needs others to accomplish the task, a median value of 20% performance deceleration was obtained. Again, this finding corresponds to the results obtained in the original analysis.

The other IPs are even more interesting in that they contain what were formerly the extremes in the range of obtained findings in the preliminary study. The absolute values fluctuated as would be expected in this type of effort (especially since the IP framework was imposed after the fact), but prediction values of the same sign reside within individual IPs. This is seen at IPs 1, 3, 4, 8, and 12, where the signs of the estimated changes in maintenance time are the same within each IP. IP 5 contains one 0 and four deceleration estimations. IP 7 holds two 0s and four deceleration values. The fact that the "extremes" fall into meaningful patterns within the IPs lends substantial credence to the utility of this model.

Looking at the way the model orders the data, it is seen that a great deal of information is at hand to predict maintenance time on tasks performed by technicians with appropriate (type and amount) experience. This is likely due to the fact that the SMES who worked through the CBP method to produce these data were experienced technicians. Six of the eight IPs in "experienced technicians" condition contain data.

Table 8. Change in Maintenance Time Between Normal and Emergency Conditions in Industry

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians IP	1	2	3	+25 4	0 -20 -20 -100 5	6	0 0 -19 -153 7	0 0 0 8
Low Experience Technicians IP	9	10	11	12	-50 13	14	15	-67 16

+ = performed faster than normal.
− = performed slower than normal.

Table 9. Change in Maintenance Time: Industry SME's Predictions of Air Force Combat Maintenance Time

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians IP	-11 -19 (1)	(2)	+33 +74 (3)	+25 (4)	-33 (5)	(6)	-13 -19 (7)	0 0 (8)
Low Experience Technicians IP	(9)	(10)	-22 (11)	-50 -66 (12)	(13)	(14)	(15)	(16)

\+ = performed faster than normal.
\- = performed slower than normal.

Table 10. Change in Maintenance Time: Air National Guard's Predictions of Air Force Combat Maintenance Time

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians IP	-20 1	2	3	4	5	6	7	8
Low Experience Technicians IP	9	-20 10	11	-40 12	13	14	15	16

+ = performed faster than normal.
− = performed slower than normal.

Table 11. Change in Maintenance Time: All SMEs' Predictions

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians	-11 -19 -20		+33 +74	+25 +25	0 -20 -20 -33 -100		0 0 -13 -19 -19 -153	0 0 0 0 0
IP	1	2	3	4	5	6	7	8
Low Experience Technicians		-20	-22	-40 -50 -66	-50			-67
IP	9	10	11	12	13	14	15	16

+ = performed faster than normal.
- = performed slower than normal.

Within the "experienced technicians" condition, it can be seen that when there is a payoff for speed in completing the task, simple tasks (IPs 3 and 4) are predicted to be performed more quickly. This holds true whether the task is performed alone or others are needed to complete it. When the task is complex and others are needed to complete it (IP 1), maintenance time is judged to be slowed (19%), even though there is a payoff for speed in accomplishing the task.

Still focusing upon experienced technicians, when there is no payoff for speed, simple tasks are predicted to take neither less nor more time when performed alone in a combat situation (IP 8 is uniformly 0). When others are needed to complete a simple task for which there is low payoff for speed (IP 7), more time is needed; the latter holds for a complex task with the same parameters (IP 5). (Both complex and simple tasks, IPs 5 and 7, received a mid-range value of nearly 20% longer time to do the task when there was no payoff for speed.)

Given even this preliminary analysis, it can be said that these four factors interact to produce distinctive combat circumstances in which maintenance time can be predicted. Maintainer performance time would be decelerated in the circumstances described by IPs 1, 5, 7, 10, 11, 12, 13, and 16. It would be accelerated in situations similar to those at IPs 3 and 4. It would show no change in a scenario such as IP 8.

V. HOW THE MODEL WOULD BE USED

The first step in utilizing the model would be for the user to match the prediction situation to the appropriate IP in the model. In order to do this, the prediction situation itself would be categorized by simply determining whether it was high or low on each of the four factors. (The reader may wish to return to Table 7 to see the IP model.)

For example, if the situation in question were high on all the factors in Table 7, IP number 1 would be the best match. If the prediction scenario were high on experience of technicians and also had a high payoff for speed, but low on the other two factors, IP number 4 would be the best match--and so on through the list.

After determining the characteristics (high vs. low) on each of the four factors and deciding upon the IP to which the prediction scenario was best matched, the data at that IP would be retrieved.

The retrieval of the data could take several forms. First, and most simply, the mean or median value of performance deceleration/acceleration could be obtained. A single value, or a mean accompanied by a standard deviation, would be useful when the user wanted only a general estimate or wanted to combine several single values into a planning exercise that required estimates for multiple cases.

On a more detailed level, the entire range of values could be obtained, thus giving more information to the user and allowing the user to see the variation in the data, the distribution, the worst case, the best case, and the model case.

Finally, the user could request the actual case descriptions (the task, the maintainer, the context in which the task was performed, etc.) from which the numerical data were derived. This would allow the user to gain even more insight into the phenomenon. Thereby, a better understanding of the causal factors that drove the predictions would be obtained. Special causes that might operate, either in the particular case the user is estimating or in analog cases, could be determined from this use of the model. This would be especially helpful if the user were going to employ the model to engage in a CBP process. In such an instance, the most closely matched case(s) at or clustered around the IP could serve as the comparison case in a CBP application.

As an example of how this tool might be utilized, imagine that the user is trying to estimate the change in maintenance time for a combat scenario in which an experienced maintainer would not enhance his or her own safety by getting the job done quickly. The task the maintainer has to accomplish in Example 1 is a simple one that requires others in order to get it done. (Table 12 describes the situation of Example 1.)

Table 12. Example 1

This situation would be characterized by:

Task Complexity	=	L
Experience of Techs	=	H
Payoff for Speed	=	L
Need for Others	=	H

This pattern of situation characteristics matches IP 7 of the model. The change in maintenance time data at IP 7 can be retrieved. The data may be used in summary form, all percentage figures may be retrieved, or the vignettes describing the cases from which the percentage of changes in maintenance time were derived may be retrieved.

Data from IP 7 are shown in Table 13 and Appendix A.

Table 13. Information About Aircraft Maintenance Time Retrieved from IP 7 for Example 1

Median = 19% deceleration.
Range = 0% - 153% deceleration.

All obtained percentages:
0, 0, 13, 19, 19, 153% deceleration.

VI. ADDITIONAL DATA COLLECTION

Additional data were collected in the summer of 1986 in an attempt to obtain information about several of the IPs for which data were unavailable. It was hoped also to get a preliminary notion of whether information collected from maintainers performing in a different environment would be similar to that obtained in the preliminary study.

Data were gathered from SMEs responsible for the maintenance of fire-fighting equipment and who had recently used it to extinguish a fire resulting from a large chemical spill. This was an extremely dangerous situation for the personnel who fought the fire and for the maintenance people who performed their repair tasks at the site of the fire. Four days were needed to extinguish the fire. Toxic gases released from the fire formed a cloud that threatened adjacent communities, several of which had to be evacuated during the course of the incident. Data were collected approximately 2 months after the incident occurred.

Only two maintenance people were involved in the incident. The data pool is therefore small--similar in number to the Air National Guard SMEs (n = 3) in the first study. However, it must be remembered that the intent of using expert judgment is not to run large numbers of subjects as in an experiment, but to capture critical information within the experience base of each expert.

The CBP method was used to lead the SMEs to a prediction of maintenance time change in an Air Force combat scenario. The two SMEs were maintenance personnel permanently employed by an urban fire department. One was a highly experienced maintenance person who also had some experience dealing with emergency situations, although these emergencies had posed no threat to his own personal safety. The other SME was less experienced in maintenance (he called himself moderately experienced), but did have experience in firefighting, which entails a considerable amount of exposure to personal danger.

The SMEs were guided through the CBP method on two separate occasions. Seven tasks were recounted and seven predictions made. Four tasks were described by the less experienced maintainer and three by the highly experienced maintenance person.

The SMEs first were asked to determine the difference in time between the normal and the emergency conditions to complete their own tasks. A hypothetical Air Force scenario was then described and the experts were asked to predict the time for Air Force maintenance personnel to complete a similar task under emergency conditions.

Each of the tasks performed in this emergency resulting from the spill was evaluated separately on each of the four factors in the model in order to determine the IP to which it should be assigned. The same procedure was followed for each prediction generated for the Air Force scenario.

Tables 14 and 15 depict the 14 data points that were obtained. Also shown in these tables are the data, from the same IPs, from the first study. As can be seen, a remarkable correspondence between the two data sets was obtained. Inspection of Table 14 (which depicts change in maintenance time between normal and emergency conditions) shows that three data points with similar signs were added to IPs 3 and 4 and a zero added to IP 8 which uniformly contains that value. Table 15 (showing fire equipment maintainers' predictions for all combat maintenance time) reveals that seven predictions were added to IPs 3 and 4, six of which were predictions of accelerated maintenance time (the seventh was a zero which does not violate the similarity of signs within the IP). Table 16 shows all data from both studies.

Of additional interest was the [illegible] obtained from these maintenance personnel on the "preparedness for the hazard" factor. It will be remembered that the first cut at the model contained five factors, only four of which were used because the fifth factor, "preparedness for the hazard," contained data for only one level of the variable. Information about this factor was obtained from the maintenance personnel who had been present at the disaster incident. These men predicted (see Table 17) a markedly slower time to complete a simple task alone for both experienced and inexperienced technicians when those technicians could not [illegible] for the hazard (IPs 20 and 28). It should be noted that these data were obtained from a small number of experts, so these findings should be regarded as tentative.

In summary of the findings obtained regarding the disaster incident, the obtained data matched extant data and filled in several IPs for which previously there were no data. The direction of change in maintenance time predictions was consistent within each IP and the absolute change values were well within the range of values obtained in the preliminary study.

SUMMARY OF THE WORK

This research was directed toward the construction of a modeling tool to describe and predict the effects of [illegible] stress on maintenance time. The original intention had been to [illegible] a mathematical model, but the type of data at hand, as well as the [illegible] study, prompted the abandonment of that notion. Instead, an identification point model was constructed.

Five factors derived from the preliminary study were used as the building blocks of the model. Each [illegible] high or low, resulting in a model containing 32 identification points. The model sequences and stores expert judgments concerning maintenance time in a combat situation. The Identification Points serve as entry points to the data stored in the model for the user to [illegible] changes in maintenance time.

The types of information that may be retrieved from this kind of model were delineated. Maintenance deceleration data can be retrieved in the form of summary statistics, ranges, and distributions. As a somewhat novel

Table 14. Match of Disaster Incident SMEs' Predictions to Those in Preliminary Study

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians IP	1	2	+43[a] +80[a] 3	+25 +50[a] 4	0 -20 -20 -100 5	6	0 0 -19 -153 7	0 0 0 0[a] 8
Low Experience Technicians IP	9	10	11	12	-50 13	14	15	-67 16

+ = performed faster than normal.
- = performed slower than normal.

[a] values obtained from actual disaster incident.

Table 15. Match of Disaster Incident SMEs' Predictions to Those in Preliminary Study

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians	-11 -19 -20		+33 +43[a] +74 +80[a]	0[a] +10[a] +25 +33[a] +50[a] +53[a]	-33		-13 +19	0 0
IP	1	2	3	4	5	6	7	8
Low Experience Technicians		-20	-22	-40 -50 -66				
IP	9	10	11	12	13	14	15	16

\+ = performed faster than normal.
\- = performed slower than normal.

[a]values obtained from actual disaster incident.

Table 16. Prepared Condition
Change in Maintenance Time: All SMEs in Both Studies

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians	-11 -19 -20		+33 +43 +43 +74 +80 +80	0 +10 +25 +25 +33 +50 +50 +53	0 -20 -20 -33 -100		0 0 -13 -19 -19 -153	0 0 0 0 0 0
IP	1	2	3	4	5	6	7	8
Low Experience Technicians		-20	-22	-40 -50 -66	50			-67
IP	9	10	11	12	13	14	15	16

+ = performed faster than normal.
– = performed slower than normal.

Table 17. Unprepared Condition
Change in Maintenance Time Between Normal and Emergency Conditions

	High payoff for speed				Low payoff for speed			
	High complexity		Low complexity		High complexity		Low complexity	
	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others	high need for others	low need for others
High Experience Technicians IP	1	2	3	-31 4	5	6	7	8
Low Experience Technicians IP	9	10	11	-100 -100 12	13	14	15	16

+ = performed faster than normal.
− = performed slower than normal.

feature, a case description of each incident that served as the comparison case also can be gleaned from this type of modeling, thereby providing users with background information from which the maintenance deceleration numbers were derived.

VIII. RECOMMENDATIONS

In further refining this model to predict the effect of stress upon maintainer performance time, what should the next steps be?

1. Full-scale data collection should occur.

2. An automated decision aid should be developed.

3. The prediction values obtained from the model should be synthesized with extant information about sortie rates, thereby enhancing the quality of the predictions on sortie rate and answering the overriding questions on this issue posed to the planner.

A full-scale study should be conducted to obtain the necessary information to fill each of the IPs of the model. Ten to fifteen data points would be collected for each IP of interest, thereby generating sufficient numbers from which to construct estimations of maintenance time.

In a full-scale study, the boundary conditions of the Air Force combat scenario would be specified for the CBP method to be used. For example: SMEs, when predicting the Air Force maintenance time, would be told that the technicians in that situation would not be highly experienced. They would be told to make their predictions about a complex task that was performed alone. The amount of preparation that would be expected for a particular type of combat situation would be specified.

In addition to the relevant causal factors derived from the present data base, other factors should be included as well. The role of sleep deprivation and fatigue would be systematically investigated. Very importantly, the issue of the quality of performance should be addressed since a task that is done incorrectly has a critical impact upon the aircraft's performance in combat.

There are groups of non-military maintenance personnel whose job it is to spearhead the cleanup work for chemical spills and other similar incidents. (Such personnel had the task of cutting open the tanker carrying the phosphorous in the incident described in the second phase of this paper.) They work in extremely hazardous situations, each of which may be somewhat unique. Consequently, preparation cannot be as extensive for them as for the SMEs (constituting the current database) in the hazardous chemical plants. The understanding of how the lack of preparation affects the performance of technical tasks in stressful conditions would be enhanced by using such a group of SMEs. Again, the non-military judgments would be augmented by those from Air Force personnel, especially with respect to quality of performance.

Since the boundary conditions of the IPs in the model can be specified beforehand, the order in which to collect data for the IPs is not rigidly defined. Consequently, special situations (IPs) that are of greatest concern to the users could be isolated and given heavy emphasis when collecting data. This could be done at any stage in the research.

The IP model outlined in the previous pages is derived, methodologically, from a completely crossed factorial design. However, it would not be unexpected that certain cells in such a design would have little meaning for Air Force planners. If this were the case, no effort need be wasted in collecting data for such conditions.

An automated decision aid could be developed. Using this decision aid would be easy and the database itself would be tied to a user's computerized information system. The decision aid would be one that users could employ while sitting in their own offices. In such an application, the user would enter into the computer pertinent information about the situation for which predictions were needed on each of the model's dimensions. (For example, would the technicians be experienced? Would the task be a complex one?) The computer would reply with the predicted change in maintenance time for the type of scenario entered by the user.

In addition, the cases from which the predictions were derived could also be presented. This would be useful if the user wanted to follow the predictions process employed by the SMEs from whom the data were collected, in order to further refine his or her own predictions. The information obtained from the prediction model could be synthesized with other Air Force databases concerning sortie rates.

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APPENDIX A: CASE DESCRIPTIONS OF AIRCRAFT MAINTENANCE TIMES RETRIEVED FROM IP 7 FOR EXAMPLE 1

0% (No change)

This SME had been a chemical plant operator for over 5 years. The job he selected as a comparison case was taking samples, which usually requires 20 minutes. In this case, he was taking samples of a chemical agent, and in the process, the fluid ran over his gloves and portions of his suit. The job still took 20 minutes per sample. He did not see any stress effect, given his level of experience.

0% (No change)

This SME was a chemical plant operator. The task he used as a comparison case was cleaning a leak that developed after a machine broke. The machine was full of a liquid which had leaked. The cleanup process took 2 hours. No effect of psychological stress was reported.

19% deceleration

This SME worked as a chemical plant operator. His duties were to destroy the chemicals. These chemicals would arrive in various types of containers. He would unpack them, remove the chemical by shearing or drilling into its container and draining the chemical, and incinerate the container in a furnace. To perform this job, he would enter a specially sealed room. He would also make repairs on equipment in the room, connect hoses, and so forth. The average worker entered the room 50 to 100 times during their employment. There was a 2-hour limit to the time a worker could spend in the chamber, and a limit of two sessions per day. Over 6,000 total entries to the room had been made without adverse effects. Operators wore the DPE ensemble described in Klein and John (1986).

The task performed in the incident he described was replacing a connecting line for chemicals. Connecting lines wear out and become blocked. The task was a routine one. Perhaps the best comparison was to performing hydraulic system repairs with the pressure off. Ordinarily he could replace a 100-foot section of line in 4 hours. Wearing the special suit, it would take him 4 hours to replace 50 feet of line. In this case, the line had been "eaten out" because of the chemical. The pumps had to be turned off, and valves closed. There were chemicals in the line and on the floor. The task required team coordination. They could see leaks. They could see chemical vapor in the air. Under these conditions, for a 50-foot section that they could usually replace in 4 hours, the task took them (and the follow-on teams) an additional 42 minutes. The extra time was needed in part because of the restrictions caused by the suits they were wearing. They could not work too fast for fear that they would tear the suits. The suits were cumbersome and heavy, although communications were not a problem. In part, the extra time was due to physical stressors such as heat and humidity. A major reason for the time increment was the emotional stresses. Personnel were more distracted by noises and sudden movements. They checked on their buddies more often. They checked their breathing apparatus more often. They got tired faster and had some difficulty concentrating on the tasks. They checked and double-checked the subtasks more carefully. In general, they tended to move more slowly and carefully.

153% deceleration

This SME had worked as a chemical plant operator for 3 years. The task he selected as the comparison case was hooking up different containers, a 15-minute task. With chemicals in the containers, the task took between 35 and 40 minutes, primarily because he kept double-checking to make sure he had completed each step and that no connections were leaking. He deliberately moved more slowly and carefully.
